Conditional Irreversibility and the Emergence of the Time Arrow from Vacuum Recomposition

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Abstract

Physical laws are, to an excellent approximation, invariant under time reversal. Yet the world we observe is not. Some processes can be reversed with arbitrary precision, while others cannot. The conventional resolution of this tension relies on statistical arguments, coarse graining, and entropy maximization, none of which identify a concrete physical mechanism that *selects* irreversibility.

This article proposes a precise and operational criterion: **irreversibility emerges exactly when the physical vacuum loses the capacity to recompose a previously coherent configuration**. When recomposition is possible, dynamics are reversible and no arrow of time exists. When recomposition fails, irreversibility appears and a time direction becomes physically meaningful. The arrow of time is therefore not fundamental but *conditional*.

The framework is developed within a medium-based description of the vacuum and is illustrated through a concrete microscopic example: the decomposition and possible recomposition of an electron into quarkbase constituents. Mathematical thresholds governing recomposability are introduced, yielding a sharp distinction between reversible and irreversible regimes without modifying the underlying equations of motion.

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1 Introduction: Reversibility and the Problem of Time

This work is not a philosophical interpretation but a constructive physical proposal, formulated in operational and falsifiable terms.

The coexistence of reversible and irreversible phenomena is one of the most persistent empirical features of physical reality.

At microscopic scales, physical processes routinely exhibit reversibility. Interference patterns can be reconstructed, coherent oscillations can be phase-reversed, and bound states can be driven back to their initial configurations with arbitrary precision. At macroscopic scales, however, the situation is radically different: thermal relaxation, diffusion, friction, and structural decay proceed irreversibly, defining a clear temporal direction.

This coexistence is not explained by the fundamental equations of physics. Classical mechanics, quantum mechanics, electromagnetism, and relativistic field theories are all invariant under time reversal, up to discrete symmetries that do not generate a macroscopic arrow of time. The equations themselves do not distinguish past from future.

The problem is therefore not mathematical but **physical**. The question is not why the equations are reversible, but why physical reality sometimes is not.

Any satisfactory explanation of the arrow of time must satisfy three non-negotiable constraints:

1. It must preserve microscopic reversibility where it is experimentally observed.
2. It must account for macroscopic irreversibility without modifying fundamental laws.
3. It must identify a *physical* mechanism, not merely a statistical tendency.

The failure of existing approaches lies not in incorrect mathematics, but in the absence of a concrete physical criterion separating reversible from irreversible regimes.

The present work does not introduce new dynamical laws, but identifies a structural criterion that determines when time-reversal-invariant dynamics cease to be physically invertible

2 Limitations of Statistical Approaches to Irreversibility

Statistical mechanics provides a powerful description of macroscopic behavior, but it does not furnish a physical mechanism for irreversibility.

The Boltzmann–Gibbs framework explains irreversibility by appealing to the overwhelming statistical dominance of high-entropy macrostates. While correct at the level of prediction, this explanation remains incomplete at the level of physical causation. Probability does not forbid a process; it merely assigns it a low likelihood.

From a physical standpoint, irreversibility requires more than improbability. It requires the loss of a capability.

Statistical arguments do not specify:

- which physical information becomes unavailable,
- where that information resides after dispersion,

- or why certain systems retain reconstructibility while others do not.

In particular, statistical entropy does not explain why a process becomes *physically impossible* to reverse rather than merely unlikely. A genuine explanation of irreversibility must identify a failure of reconstructibility grounded in the physical substrate itself.

3 Vacuum Structure and Coherent Reconstruction

3.1 The Vacuum as a Physical Medium

We adopt a minimal but decisive ontological assumption: the vacuum is not an abstract background, but a continuous physical medium capable of storing, transmitting, and reorganizing physical information.

Let the vacuum be described by a scalar field $\Psi(\mathbf{x}, t)$ with well-defined mechanical properties, including pressure response, coherence length, and characteristic propagation speed. Within this picture, physical objects correspond to stable or metastable configurations of this medium.

This assumption does not modify known equations of motion. It specifies the physical meaning of their degrees of freedom.

Within this framework, the central property governing reversibility is not energy or entropy, but **recomposability**.

3.2 Recomposable Coherence

A configuration is said to possess *recomposable coherence* if the vacuum retains sufficient geometric, phase, and topological information to reconstruct the configuration after perturbation.

Recomposable coherence is an operational concept. It is not defined by abstract symmetry, but by the physical ability of the medium to reassemble a prior structure.

Recomposability can fail through several mechanisms:

- spatial dispersion beyond a coherence length,
- phase decoherence beyond a correlation time,
- excitation of additional uncontrolled modes of the vacuum.

The causes are continuous, but the outcome is binary: either recomposition occurs, or it does not.

3.3 A Constructive Criterion for Recomposability

Let a coherent structure be characterized by N compact constituents with positions $x_i(t)$ and phases $\phi_i(t)$. We define a recomposition functional:

$$\mathcal{R}(t) = \int_V \left| \sum_{i=1}^{N} \Psi_i(\mathbf{x}, t) - \Psi_{\text{orig}}(\mathbf{x}) \right|^2 d^3x. \tag{1}$$

Recomposition is possible if and only if there exists a finite time t_r such that

$$\lim_{t \to t_r} \mathcal{R}(t) = 0. \tag{2}$$

This requires the simultaneous satisfaction of three conditions:

1. **Spatial coherence**:
$$|x_i - x_j| < \ell_c \quad \forall i, j. \tag{3}$$
2. **Phase coherence**:
$$|\phi_i - \phi_j| < \Delta\phi_c. \tag{4}$$
3. **Mode closure**:
$$\sum_k E_k^{\text{excited}} < E_c. \tag{5}$$

Failure of any condition prevents recomposition. Irreversibility is thus defined constructively, not probabilistically.

4 Microscopic Case Study: Electron Decomposition

Consider an electron modeled as a coherent vacuum structure composed of 13 quarkbase units arranged in a stable resonant configuration.

When perturbed, this structure may decompose into its constituents. Two distinct regimes arise.

4.1 Coherent Decomposition

If the quarkbases remain within the coherence radius ℓ_c, maintain phase correlation, and do not excite higher vacuum modes, then there exists a finite recomposition time t_r such that

$$\mathcal{R}(t_r) = 0. \tag{6}$$

The electron reforms. The process is fully reversible. No arrow of time is generated.

4.2 Dispersive Decomposition

If the quarkbases separate beyond ℓ_c, lose phase correlation, or excite excess vacuum modes, then

$$\forall t, \quad \mathcal{R}(t) > \varepsilon > 0. \tag{7}$$

Recomposition never occurs. The process becomes irreversible. Nothing has changed in the equations of motion; only the state of the vacuum has changed.

5 Thresholds in Reversible Dynamics

Irreversibility is not an absolute attribute of physical processes. It is a threshold phenomenon arising from the finite recomposition capacity of the vacuum medium.

Let ℓ_c denote the spatial coherence length of the vacuum, τ_c its phase-correlation time, and E_c the maximum energy that can be redistributed without exciting non-recomposable modes. These parameters are not arbitrary; they are determined by the dispersion relation and nonlinear response of the vacuum field $\Psi(\mathbf{x}, t)$.

A process remains reversible if and only if the following inequalities are satisfied throughout its evolution:

$$\max_{i,j} |x_i - x_j| < \ell_c, \qquad \Delta t < \tau_c, \qquad E_{\text{exc}} < E_c. \tag{8}$$

When any of these thresholds is exceeded, recomposition fails and irreversibility emerges.

This formulation explains why microscopic systems often remain reversible while macroscopic systems do not. The difference is not qualitative, but quantitative: macroscopic systems exceed recomposition thresholds by many orders of magnitude.

5.1 Structural Versus Statistical Irreversibility

The irreversibility described here is structural rather than statistical. It does not arise from the improbability of a reverse trajectory, but from the impossibility of reconstructing the original configuration using the degrees of freedom accessible to the vacuum.

This distinction is crucial. Statistical mechanics describes distributions over trajectories. Recomposability describes the existence of trajectories.

Once recomposition fails, the reverse trajectory ceases to exist as a physically realizable process, regardless of its mathematical admissibility.

6 Operational Criterion for Time-Asymmetric Dynamics

Within the recomposability framework, the arrow of time admits a precise operational definition.

6.1 Definition of the Time Arrow

A physical process exhibits a time arrow if and only if the vacuum cannot recompose the initial configuration from the final state using its dynamically accessible degrees of freedom.

This definition does not attribute directionality to time itself. Instead, it identifies time direction as an emergent property of physical processes that have lost reconstructibility.

6.2 Time Symmetry Without Reconstructibility

Time-reversal invariance of the equations of motion guarantees the existence of inverse trajectories in the full state space. However, the physical realization of these trajectories requires access to all degrees of freedom involved.

Once information has leaked into non-recomposable vacuum modes, the inverse mapping exists mathematically but cannot be physically implemented. Time symmetry of the laws is preserved; time asymmetry of physical processes emerges.

7 Reversibility at Different Descriptive Levels

A frequent objection to medium-based explanations of irreversibility is that the combined system—vacuum plus all excitations—remains globally reversible.

This objection is correct but irrelevant.

Let the full vacuum state be represented by

$$\Omega(t) \in \mathcal{H}, \tag{9}$$

where $\mathcal{H}$ is the infinite-dimensional state space of the vacuum field and its excitations. The microscopic dynamics define an invertible flow

$$\Omega(t) = \Phi_t(\Omega_0), \qquad \Phi_{-t} = \Phi_t^{-1}. \tag{10}$$

Physical reversibility, however, depends not on Φ_t, but on the existence of a physically accessible inverse mapping.

7.1 Decomposition of Accessible and Inaccessible Degrees of Freedom

We decompose the state space as

$$\mathcal{H} = \mathcal{H}_{\mathrm{R}} \oplus \mathcal{H}_{\mathrm{N}}, \tag{11}$$

where $\mathcal{H}_{\mathrm{R}}$ contains recomposable degrees of freedom and $\mathcal{H}_{\mathrm{N}}$ contains non-recomposable ones.

Define the projection

$$\Pi_{\mathrm{R}} : \mathcal{H} \to \mathcal{H}_{\mathrm{R}}. \tag{12}$$

The physically relevant evolution is given by

$$\Omega_{\mathrm{R}}(t) = \Pi_{\mathrm{R}} \Phi_t(\Omega_0). \tag{13}$$

Once a trajectory populates $\mathcal{H}_{\mathrm{N}}$ beyond threshold, $\Omega_{\mathrm{R}}(t)$ ceases to be invertible. Irreversibility thus arises from loss of invertibility under projection, not from loss of invertibility of the fundamental dynamics.

7.2 Resolution of Loschmidt's Objection

Loschmidt's paradox assumes that reversing all microscopic velocities suffices to reverse any process. This assumption fails when a system has populated degrees of freedom that cannot be phase-reversed or recollected by the vacuum.

While the inverse trajectory exists in $\mathcal{H}$, it is physically unrealizable once recomposition thresholds are exceeded. The paradox dissolves without modifying the equations of motion.

8 Compatibility with Liouville's Theorem and Quantum Unitarity

Liouville's theorem guarantees conservation of phase-space volume for Hamiltonian systems. Quantum unitarity guarantees conservation of norm in Hilbert space. Neither theorem implies physical reconstructibility.

Phase-space volume conservation applies to the full space $\mathcal{H}$, not to its projected subspace $\mathcal{H}_{\mathrm{R}}$. The projection Π_{R} is not measure-preserving, allowing effective volume contraction in the accessible sector.

In quantum language, global information is preserved, but operationally accessible information is not. Once phase information disperses into $\mathcal{H}_{\mathrm{N}}$, recomposition becomes physically impossible despite unitarity.

This distinction resolves the apparent conflict between irreversibility and fundamental conservation laws.

9 Poincaré Recurrence and Its Physical Limits

The Poincaré recurrence theorem applies only to systems with finite phase-space measure and bounded trajectories.

A physical vacuum supporting continuous fields and radiative modes does not satisfy these conditions. Once excitations propagate into delocalized vacuum modes, the effective phase space becomes unbounded, and recurrence times diverge beyond any physical relevance.

Recurrence therefore does not guarantee recomposition once coherence has been lost.

10 Inertia as a Reversible Vacuum Response

Within the recomposability framework, inertia acquires a concrete physical interpretation. Inertia is not an intrinsic property of matter, nor a primitive constant introduced by hand. It is a reversible response of the vacuum medium to deformation of a coherent configuration.

Consider a coherent structure represented by a configuration

$$\mathcal{S}(t) \subset \mathcal{H}_{\mathrm{R}}. \tag{14}$$

An external force attempts to accelerate this structure, inducing a time-dependent deformation

$$\mathcal{S}(t) \to \mathcal{S}(t + \delta t). \tag{15}$$

This deformation requires the vacuum to redistribute phase gradients and mechanical stress in order to preserve recomposable coherence. The resistance encountered is proportional to the rate at which this redistribution must occur.

Inertial resistance therefore emerges as

$$\mathcal{I} \sim \frac{d}{dt}\Big(\text{vacuum recomposition load}\Big), \tag{16}$$

where the recomposition load measures the vacuum effort required to maintain coherence under acceleration.

Crucially, inertia alone does not generate irreversibility. As long as recomposition remains possible, acceleration and deceleration are symmetric processes. The inertial response of the vacuum is fully reversible.

10.1 Distinction Between Inertia and Dissipation

The distinction between inertia and dissipation is structural. Inertia corresponds to reversible redistribution of vacuum stress. Dissipation corresponds to irreversible leakage into non-recomposable modes.

This explains why inertial motion does not define an arrow of time, whereas dissipative motion does.

11 Dissipation as Irreversible Vacuum Recomposition

Dissipation arises when recomposition ceases to be coherent.

Consider a macroscopic body undergoing friction. Microscopically, friction corresponds to the excitation of increasingly fine-scale vacuum modes. These excitations propagate away from the coherent structure and populate $\mathcal{H}_{\mathrm{N}}$.

As a result:

- phase information disperses irreversibly,
- spatial correlations are destroyed,
- the recomposition functional $\mathcal{R}(t)$ saturates at a nonzero value.

Energy remains globally conserved. What is lost is the ability of the vacuum to reconstruct the initial coherent configuration.

Dissipation is therefore the physical manifestation of recomposition failure. It necessarily generates a time arrow because the reverse process cannot be physically realized.

11.1 Quantitative Leakage and Scaling Behavior

Let $\Gamma(N)$ denote the rate at which a system with N interacting degrees of freedom leaks into $\mathcal{H}_{\mathrm{N}}$. For generic interactions,

$$\Gamma(N) \sim \Gamma_0 e^{\alpha N}, \qquad \alpha > 0. \tag{17}$$

For macroscopic N, leakage is effectively instantaneous. Recomposability is destroyed on timescales far shorter than any experimental resolution, enforcing irreversibility.

This scaling explains why macroscopic irreversibility is inevitable without invoking new physics.

12 Emergence of Causality from Recomposition Constraints

Macroscopic causality presupposes irreversibility. Causes precede effects because the physical world cannot reconstruct future macroscopic states from present ones.

Within the recomposability framework, causality emerges as a consequence of structural constraints on reconstruction.

12.1 Causal Ordering as an Emergent Property

In regimes where recomposition is possible, time symmetry holds and causal ordering is not enforced. This is precisely the regime of microscopic reversible dynamics.

In regimes where recomposition fails, inverse reconstruction becomes physically impossible. Once this occurs, temporal ordering becomes strict and causal structure emerges.

Causality is therefore not fundamental. It is an emergent ordering principle imposed by recomposition failure.

12.2 No Conflict with Relativistic Causality

This emergent causality does not conflict with relativistic causality. The vacuum recomposition constraints operate within the causal structure defined by relativistic field propagation. They do not introduce superluminal influences or causal paradoxes.

13 Measurement as an Irreversible Physical Process

Measurement is inherently irreversible because it produces a stable record.

In the present framework, a measurement corresponds to a controlled process in which a microscopic system becomes irreversibly coupled to macroscopic degrees of freedom. This coupling drives the joint configuration into $\mathcal{H}_{\mathrm{N}}$.

Once this transition occurs:

- superposed phase relations cannot be recomposed,
- the outcome becomes fixed,

- reverse evolution is physically impossible.

Measurement irreversibility is therefore not postulated. It follows directly from recomposition thresholds.

13.1 Decoherence as Loss of Recomposable Phase Information

Decoherence corresponds to the gradual loss of phase coherence as a system interacts with its environment. In recomposability terms, decoherence marks the progressive leakage of phase information into non-recomposable vacuum modes.

Once decoherence exceeds threshold, recomposition becomes impossible and classical behavior emerges.

14 Absence of the Time Arrow in Isolated Microscopic Systems

Isolated microscopic systems frequently exhibit time-symmetric behavior. This is not an anomaly, but a confirmation of the recomposability criterion.

Such systems:

- involve few degrees of freedom,
- remain spatially localized,
- do not excite dense continua of vacuum modes.

Their trajectories remain confined to $\mathcal{H}_{\mathrm{R}}$, and the recomposition functional remains close to unity:

$$\mathcal{R}(t) \approx 1. \tag{18}$$

No arrow of time emerges because no recomposition failure occurs.

15 Thermodynamic Irreversibility

Thermodynamic irreversibility emerges naturally once recomposable coherence is lost across many degrees of freedom.

In the present framework, entropy increase does not represent a fundamental tendency of nature, but the cumulative effect of recomposition failure. As a system evolves, an increasing fraction of its dynamical content leaks into non-recomposable vacuum modes, enlarging the set of physically inaccessible configurations.

15.1 Entropy as an Index of Non-Recomposable Occupation

Let S denote thermodynamic entropy. Within the recomposability framework, entropy increase corresponds to the monotonic growth of occupation in $\mathcal{H}_{\mathrm{N}}$:

$$\frac{dS}{dt} \propto \frac{d}{dt}\Big(\dim \mathcal{H}_{\mathrm{N}}^{\mathrm{occupied}}\Big). \tag{19}$$

The second law of thermodynamics follows directly: once recomposable coherence is lost, it cannot be recovered by the vacuum alone. Entropy does not decrease because recomposition is structurally forbidden, not because it is statistically unlikely.

15.2 Irreversibility Without Fundamental Asymmetry

This interpretation preserves the time-reversal invariance of microscopic laws. No asymmetric boundary conditions or stochastic postulates are required. Thermodynamic irreversibility is an emergent consequence of vacuum dynamics under complexity amplification.

16 Classicality as a Non-Recomposable Regime

The emergence of classical behavior is closely tied to irreversibility.

Classical systems are precisely those systems whose trajectories almost immediately exceed recomposition thresholds. Once this occurs, phase relations cannot be recovered and interference effects are suppressed.

16.1 Loss of Phase Accessibility

In recomposability terms, classicality corresponds to permanent confinement of dynamics to $\mathcal{H}_{\mathrm{N}}$-dominated trajectories. Phase information disperses into inaccessible modes and ceases to influence observable evolution.

This explains why classical trajectories appear deterministic and time-directed despite underlying reversible laws.

16.2 No Measurement Postulate Required

Classical behavior does not require a special measurement postulate. It arises dynamically when recomposable coherence is destroyed by interaction with a sufficiently complex environment.

17 Cosmological Emergence of the Time Arrow

The arrow of time observed on cosmological scales can be understood within the same recomposability framework.

Early-universe conditions are expected to favor high coherence, limited mode excitation, and low occupation of $\mathcal{H}_{\mathrm{N}}$. Under such conditions, large-scale dynamics may remain reversible over extended periods.

As structure forms and interactions proliferate, recomposition thresholds are exceeded at increasing scales. The vacuum progressively loses the ability to reconstruct earlier global configurations.

17.1 No Dependence on Special Initial Conditions

This account does not require finely tuned initial conditions. The emergence of a cosmological time arrow follows from the natural growth of complexity and mode occupation in an evolving vacuum medium.

The arrow of time thus emerges dynamically rather than being imposed at the origin of the universe.

18 Synthesis of Results

The recomposability framework provides a unified explanation for a broad class of phenomena traditionally treated as distinct.

- **Microscopic reversibility** arises when recomposable coherence is preserved.
- **Macroscopic irreversibility** arises when recomposition fails.
- **Thermodynamic entropy** measures cumulative recomposition loss.
- **Inertia** reflects reversible vacuum response.
- **Dissipation** reflects irreversible vacuum leakage.
- **Classicality and causality** emerge once recomposition thresholds are exceeded.

No additional principles are introduced. The framework respects established symmetries and conservation laws.

19 Discussion and Open Directions

While the core mechanism is complete, several directions merit further investigation.

19.1 Quantitative Determination of Thresholds

Precise determination of coherence lengths, phase-correlation times, and excitation thresholds requires detailed modeling of vacuum response functions. Such refinements would enable quantitative predictions for mesoscopic systems.

19.2 Experimental Probes

Systems near recomposition thresholds may exhibit partial reversibility, delayed recomposition, or controlled decoherence. Experimental exploration of such regimes would provide direct tests of the framework.

19.3 Engineered Vacuum Environments

Structured environments may modify recomposability thresholds, opening the possibility of manipulating irreversibility and coherence at intermediate scales.

20 Concluding Remarks

The arrow of time is not a fundamental feature of temporal evolution. It is a physical consequence of the vacuum's finite capacity to reconstruct coherent configurations.

When recomposition is possible, physical processes are reversible and time is symmetric. When recomposition fails, irreversibility appears and time acquires direction.

The arrow of time is therefore not imposed. It is **earned** through the dynamics of a physical medium.

No statistical coarse graining or interpretative postulate is required at any stage.

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